

Effects of Long-Term Flow Variation on Microhydropower Energy Production in Pressure Reducing Valves in Water Distribution Networks

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1 **Effects of Long-term Flow Variation on Micro-Hydropower Energy Production in Pressure**
2 **Reducing Valves in Water Distribution Networks.**

3 Jennifer Brady¹, John Gallagher², Lucy Corcoran³, Paul Coughlan⁴ Aonghus McNabola⁵

4

5 **ABSTRACT**

6 Incorporating micro-hydropower (MHP) turbines within water supply networks has the potential to
7 improve the economic and environmental sustainability of the sector. However, long-term flow and head
8 variations in water networks is a key risk factor which increases turbine performance uncertainty in the
9 medium-to-long term, potentially impacting on the investment payback period. Using high-resolution
10 historical flow and head data across a number of pressure reducing valve sites in water networks in
11 Ireland, this study presents an assessment of the impact of flow and head variations on turbine efficiency
12 and power output over a twenty year period. Results indicated that pumps-as-turbines (PATs) represent
13 a viable low-cost option over the long-term, at sites with smaller power output potential. Where flow
14 and head rates displayed considerable fluctuation, the integration of a two-PAT configuration could

15 improve operating efficiency and maximise power output. This design strategy opens up the opportunity
16 to conduct energy recovery from sites which may previously have been considered unsuitable for MHP.

17

18 ***Keywords***

19 Water Supply; Micro-hydropower; Energy recovery; Pressure reducing valve; Pump-as-turbine

20

21 **1 Introduction**

22 A continuous high quality water supply is a vital facet of effective societal and economic development
23 across nations. Such continuity of service is predicated on sustained energy security and affordability
24 into the future. The water industry is particularly vulnerable within this context as water abstraction,
25 treatment and distribution are energy intensive processes. Globally, 2-3% of total energy consumption is
26 associated with pumping and treating water (Kwok et al. 2010). The UK water industry for example,
27 utilises approximately 3% of total energy demand (Environment Agency, 2009) emitting over 5 million
28 tonnes of CO₂ emissions annually (DEFRA, 2008). Concurrently, the overall cost of water provision is
29 rising due to increased energy costs (Zilberman et al. 2008). In Ireland, water service provision costs
30 have been increasing by approximately 7.5% per year since 2007 and key drivers include higher capital
31 investment requirements, rising energy costs together with more stringent regulatory compliance in
32 terms of both national and European Union (EU) legislation (DoEHLG, 2010). Accordingly, there is a
33 pressing need to achieve greater efficiencies across water infrastructure in conjunction with the
34 integration of economically viable renewable energy technology solutions.

35 Opportunities exist for energy efficiencies across the entire water supply chain. A breakdown of
36 energy demand across water service provision reveals that water distribution accounts for 45% of total
37 energy consumption (Daigger, 2009). Many water utilities are now incorporating renewable

38 diversification with a range of energy applications including: hydropower, wind turbines, solar power,
39 the generation of energy in wastewater treatment facilities (Kwok et al. 2010; UKWIR 2010).

40 In terms of hydropower, large-scale installations are widespread on a global scale, yet, micro-
41 hydropower (MHP) at various water infrastructure locations has experienced limited market penetration
42 to date (Gaius-obaseki 2010). Vilanova and Balestieri (2014) note that the use of hydraulic turbines
43 inserted within water distribution networks represents one of the most complex forms of energy
44 recovery in water supply systems. There is a need to address identified barriers to the uptake of MHP in
45 an effort to strengthen the investment case for greater acceptance of this technology in the water industry
46 (McNabola et al., 2014a). One such barrier is long-term network flow and head variation and their
47 potential impact on the operational efficiency of turbines.

48 Turbines are designed for a relatively stable flow rate, yet flow variation can occur diurnally,
49 seasonally and over the long-term which can impact on efficiency and thus capital payback (Sitzenfrei
50 and Rauch, 2015). Carravetta et al. (2014a) highlight the importance of flexibility within an energy
51 production system given that operating conditions can vary due to network flow variation during its life
52 cycle. Climate change, population growth, leakage rates, water pricing and economic activity have all
53 been shown to have an impact on long-term flow and head variations in water distribution networks
54 (Corcoran et al., 2016).

55 Considering the initial high capital investment requirement, there is a need to ensure the long-term
56 viability of a MHP installation. Accordingly, this paper aims to investigate long-term fluctuations in
57 flow rates and head over time at three potential hydropower locations within the water supply network
58 of Dublin City (Ireland). The viability and operational resilience of three turbine options including a
59 Kaplan and pumps-as-turbines (PATs) are assessed and outcomes are compared in terms of energy
60 recoverable, payback periods and gross income. The paper concludes with engineering design
61 recommendations regarding future MHP installations in light of potential increases in flow/head
62 variability into the future.

63 2 **Hydropower Energy Recovery in Water Networks**

64 The potential for energy recovery via MHP has been identified within water supply networks at
65 points of high flow or surplus hydraulic head which otherwise needs to be dissipated for pressure
66 management purposes (Vicente et al. 2016). Such applications include flow control valves, pressure
67 reducing valves (PRVs), storage/service reservoirs, break pressure tanks and wastewater treatment plants
68 (Williams et al. 1998; Saket 2008; Gaius-obaseki 2010; Corcoran et al. 2012; Power et al. 2014;
69 McNabola et al. 2014a; Samora et al. 2016). This excess energy can be recovered and converted into
70 electricity without reducing the level of service to customers.

71 Specifically, pressure reducing valves (PRVs) have been identified as a large untapped resource and
72 Carravetta et al. (2014b) note that the number of PRVs is increasing across networks as they can reduce
73 leakage and delay the need for expensive rehabilitation works. Gaius-obaseki (2010) states that up to
74 85% of wasted energy can be recovered through replacement of a PRV with a turbine or alternatively
75 through installing a turbine and a PRV in parallel. However, technological and economic viability
76 barriers exist which to date have prevented the exploitation of this potential energy saving.

77 Many studies have identified the potential for pumps-as-turbines (PATs) to produce energy in water
78 networks (Williams 1996; Ramos and Borga 1999; García et al. 2010; Carravetta et al. 2012; Carravetta
79 et al. 2014b; Fecarotta et al. 2015). PATs, where a water pump is run in reverse, have a cost advantage
80 over conventional turbines for small scale energy generation, as a wide range of pump sizes are mass
81 produced. Furthermore, they are easy to install (Williams 1996) and spare parts are widely available
82 (Agarwal 2012). In contrast, hydraulic turbines are considerably more expensive due to fact that they are
83 specifically designed for each site. However, they display greater efficiencies over a wider range of flow
84 and head rates when compared to PATs. Additionally, PATs do not possess a regulation device so this
85 must be included during installation where pressure control is required (Carravetta et al. 2014a). To date,
86 real scale installation of hydraulic turbines and PATs within water distribution networks remains
87 somewhat limited. There are evident challenges when installing either turbine option within the small

88 distribution network setting, specifically the smaller power potential across sites and high variability in
89 hydraulic characteristics when compared to larger transmission pipelines (Giugni et al. 2014; Carravetta
90 et al. 2014b). Furthermore, previous research has established that a mere 10% change in flow rate at a
91 small sized plant can increase the payback period and render a MHP project unsuitable (McNabola et al.
92 2014b).

93 Given that MHP installations typically have an investment payback period of 10 years, there is a
94 need to assess future flow uncertainties into the medium-to-long term. Research regarding the impact of
95 demand uncertainty and long-term flow variation specifically on turbine efficiency is relatively limited.
96 Sitzenfrei and von Leon (2014) utilised ten years of hourly water consumption data in a simulation
97 model for the design and optimisation of a small hydropower system testing various turbine sizes.
98 Additional research involved the use of this long-time simulation model to analyse the effects on a small
99 hydropower system in which a control mechanism for the device was optimised in order to maximise
100 profits (Sitzenfrei et al. 2014). More recently, Sitzenfrei and Rauch (2015) assessed the impact of
101 different future population and demand scenarios on the performance of a small Pelton hydropower
102 system in Austria and the authors stressed that disregarding both long-term demand patterns and demand
103 uncertainty hinders the attainment of a realistic evaluation of potential profits. Similarly, Colombo and
104 Kleiner (2011) highlight the importance of considering changes in demand over time. Their study
105 probabilistically analysed the feasibility of energy recovery via micro turbines and identified that diurnal
106 and seasonal demand fluctuations can significantly impact project return.

107 The optimal choice of turbine is dictated by the flow and pressure range of the site (Gaius-obaseki,
108 2010) and high variability in user demand can significantly impact turbine suitability. Sitzenfrei et al.
109 (2014) comment that within a 20-year period, water infrastructure and small hydropower installations
110 can be significantly impacted by population dynamics and water use. Limited research has analysed the
111 performance and operational efficiency of turbines using historical long-term flow data, and no
112 investigations have examined the long-term performance of PATs to date. Accordingly, this study aims

to fill this gap through assessment of historical flow and head variation using up to twenty years of high-resolution data across three PRV sites within a water distribution network and analysing the resulting impact on available volumes of water for energy production across a number of different turbine design scenarios. A near-optimal MHP design strategy for small capacity sites, in terms of improving turbine efficiency performance over the long-term, is subsequently developed and discussed.

3 Methodology

3.1 Simulation of long-term turbine performance

The study firstly analyses the extent of long-term fluctuations in flow and head across three PRV sites over a period of up to 20 years. It was anticipated that due to population and economic growth, user demand and thus flow rates would change significantly over the time period across the three sites.

The first year of data in each historical record was utilised to establish a design flow for a hypothetical turbine installation at each location, assuming year one in the historical dataset represented the present day. It is common practice in the design of MHP installations in both run-of-river and water network settings to establish the turbine design flow, Q_0 , based on the average flow from one year of flow data. However as this paper aims to demonstrate, such practices are fraught with inaccuracies, most particularly in water distribution.

The paper presents a theoretical simulation of the potential performance of varying turbine design options at the three PRV sites over the intervening years in the historical record (16-19 years), assuming that these data represent future flow rates. Turbine efficiencies were evaluated over this long-term period in response to flow and head variation. Total reductions in CO₂ emissions were also estimated.

3.2 Turbine Design Scenarios

137 The three turbine design scenarios investigated are displayed in Figure 1. Firstly, a traditional Kaplan
138 turbine was selected due to its wide high-efficiency range (see Figure 3) and suitability for the low-head
139 and high-flow conditions of the three PRVs. Secondly, a single PAT was assessed at each site. Whilst a
140 PAT possesses a narrower high-efficiency range, it is considerably lower in cost when compared to a
141 conventional hydraulic turbine.

142

143 **Figure 1.** Installation schemes of three turbine scenarios; a traditional Kaplan turbine, PAT and two
144 PATs in parallel (Adapted from Carravetta *et al.* (2012)).

145 Considering this low cost, a third scenario incorporated two differently sized PATs in which flow
146 would be directed through either the larger PAT with a design flow based on the average flow rate in
147 year 1 or alternatively through the smaller sized PAT designed for 50% less than that design flow.
148 Therefore, the optimal choice of PAT in scenario three was dependent on the incoming flow rate and
149 flow was switched to the smaller PAT when this would produce a higher power output. This two-PAT
150 scenario was included in order to increase efficiency and power generation potential. Both PAT systems
151 also included the concept of a hydraulic regulation device to control downstream pressure as described
152 by Carravetta et al. (2014a). All turbine scenarios incorporated a by-pass system to prevent disruption to
153 the supply service in the event of maintenance requirements or failure of the turbine.

154

155 3.3 Case Study Area - Dublin

156 This study builds on previous research regarding the MHP energy recovery potential of the Dublin water
157 supply network (Corcoran et al. 2012, 2013, 2016; McNabola et al. 2014b) through analysis of a subset
158 of PRV sites in the network (see Figure 2). In this paper, the viability of three turbine configurations

159 comprising either a hydraulic turbine or a PAT is investigated with the aim of exploring their operational
160 efficiencies and economic suitability over the long-term.

161

162 **Figure 2.** Map of the Dublin region displaying the location of the three pressure reducing valves used in
163 the case study.

164 High resolution telemetry data of flow and head at 15 minute intervals collected by Dublin City Council
165 was utilised for simulation of turbine performance across three PRV sites: Thomas Court; Blackhorse
166 Bridge; and Merrion Gates, over 20 years (up to 700,800 measurements). These sites were selected as
167 they possessed different flow and head characteristics together with varied power output potential, as
168 outlined in Table 1. Head data comprised both inlet and outlet head readings. The availability of data
169 varied across sites ranging from 17 years up to 20 years (1993 to 2013).

170 Thomas Court was located on a section of the network which feed a large industrial user of water. This
171 user was the largest water user in Dublin and required a high flow rate. High flow and pressure was
172 delivered to this location to meet processing needs. The Blackhorse bridge PRV was located in a mainly
173 residential area, while Merrion Gates was located adjacent to a large hospital. Each site served quite
174 differing water demand types, which partly explains the reasons for differing head and flow values
175 shown in Figure 4. In addition to this, each of the 3 valves are located in differing sections of Dublin,
176 one in the city centre, one in the south and one in the north-west. The cumulative demands from source
177 to supply in each area was different.

178

179 *3.4 Simulation of Power Output Potential and Estimation of Return of Investment*

180 The three sites differed regarding their estimated power potential. Table 1 displays the average flow rate,
181 head and estimated power potential across the PRVs.

182

183 **Table 1.** An overview of flow, head and power output estimates for three PRVs in Dublin. Power
184 estimates were based on varying Kaplan turbine efficiencies, where the turbine design flow/head was
185 assumed to be the average of the data from year 1 of the record.

186

187 The potential power output at each site was simulated for every 15 minute interval within the 20-year
188 dataset using equation (1), where P represents the power output (kW), Q is the flow rate through the
189 turbine (m^3/s), ρ is fluid density (kg/m^3), g is acceleration due to gravity, H is the available head (PRV
190 head drop) at the turbine (m) and e_o represents the overall system efficiency.

191
$$P = Q\rho gHe_o \quad (1)$$

192 Therefore flow and head varied according to their measured input values (head was taken as the
193 difference between input and output head at the PRV i.e. available excess head). Overall system
194 efficiency included a variable turbine efficiency value together with generator and transmission loss
195 efficiencies estimated to be 85% and 98% respectively (Power et al., 2014). Turbine rotational speed and
196 therefore efficiency varied according to the extent of deviations in the instantaneous flow and head
197 measurements from their design values (selected as the average flow and average head in year 1 of the
198 data records). Turbine efficiency curves, adapted from Corcoran et al. (2013) and Ørke (2010), were
199 used to quantify these changes as shown in Figure 3. A sixth-degree polynomial equation was fitted to
200 data in each efficiency curve and used to estimate of overall system efficiencies for each turbine option
201 according to Equation 2. In terms of historical demands and turbine design, the average flow rate over
202 the first year of available data at each PRV site was utilised as the design flow criteria for each turbine

option. For the two-PAT scenario, the design flow for the second smaller PAT was chosen as 50% less than the average annual flow rate.

Figure 3. Overall system efficiency curves for the Kaplan turbine and PAT, assuming generator and transmission loss efficiencies of 85% and 98% respectively.

$$e_0 = e_{turbine} \times e_{generator} \times e_{transmission} \quad (2)$$

Where $e_{turbine}$ is the instantaneous turbine efficiency; $e_{generator}$ is the generator efficiency; and $e_{transmission}$ is the transmission efficiency.

In terms of assessing economic feasibility, a payback period approach was applied where the payback period equals the investment cost divided by the net annual revenue (ESHA, 2004). In general, MHP projects which exceed a payback period of 10 years are not considered viable by water utilities (McNabola et al., 2014b). The overall costs of an MHP installation comprise the initial installation costs (design, construction, installation and commissioning) and subsequent operation and maintenance costs. Generally, MHP projects require large upfront investment costs with low recurring costs thereafter. Installation costs for an MHP turbine are mainly site specific and can differ depending on the amount of civil works needed and proximity to the grid. It has been estimated that capital costs for the installation of micro-hydropower are in the range of £3,000 to £6,000 per kW installed and costs decrease with an increase in capacity or for higher head turbines (Gaius-obaseki, 2010). Similarly, MHP turbine installation costs in America are estimated to be in the region of \$3,500-\$7,000/kW whilst maintenance costs are approximately \$2,000 annually (Colombo and Kleiner, 2011). In the present study, installation costs for the Kaplan turbine were estimated using an empirical formula developed by Ogayar et al. (2009) based on power output and hydraulic head (Equation 3). The cost per kW for a PAT was

226 estimated at €350/kW according to previous research undertaken by Carravetta et al. (2013), as no cost-
227 power-head function is currently available for PATs.

228

$$229 \quad \text{Kaplan Cost} = 31196.P^{0.41662}.H^{-0.113901} \quad (3)$$

230 Where *Kaplan cost* represents the euro value of electromechanical equipment; *P* is the power output
231 (kW); and *H* is the head (m). Both of these costs estimates relate to the electromechanical equipment
232 only and do not incorporate civil construction works. In the present study it was assumed that the turbine
233 cost represented 30% of total installation costs, signalling that civil and construction works amounted to
234 70% of total expenditure, as per previous research findings (Gallagher et al. 2015). An additional fixed
235 maintenance costs of €1,496 (\$2,000) per annum (Colombo and Kleiner 2011) was also incorporated in
236 the economic analysis.

237 It was assumed that the electricity generated would be utilised on site rather than connecting to the
238 grid, thus reducing the total investment requirement. This option has previously been found to be more
239 economically advantageous in Ireland due to low REFIT rates for MHP (Corcoran et al. 2013).
240 Accordingly, annual power generation was multiplied by the end user industrial price of electricity for
241 2013 of €0.137/kWh, in order to establish annual electricity savings (Eurostat 2014b). In terms of the
242 environmental benefit, equivalent CO₂ emissions from electricity generation were calculated based on
243 2013 figures of 528 g per kWh in Ireland (SEAI, 2013).

244

245 **4 Analysis and Results**

246 *4.1 Long-term Flow Variation*

247 Average annual flow and head data for each PRV site are displayed in Figure 4. The analysis revealed
248 considerable variability between sites and highlights the influence of local water demands in each area.
249 The Merrion Gates PRV, for example, served a nearby hospital which would possess a different demand
250 pattern when compared to flow feeding residential or commercial districts. Whilst it would be
251 reasonable to forecast gradual increases in demand due to expected economic and population growth, the
252 data indicate that average flow rates decreased substantially during the 1990s. Given that turbines are
253 designed (and would be selected) according to a particular performance band, this reduction in flow rate
254 could impact turbine efficiency and thus energy recovery. During the 2000s, a general increasing trend
255 in demand was evident in line with the Irish economic boom period but a second prolonged decrease
256 was observed at the smallest PRV site, Merrion Gates. Such deviation creates difficulties when
257 attempting to optimise the turbine design flow. In contrast to flow rates, long-term variations in head
258 were less extreme across sites. Figures S1 to S2 in the supplementary materials sections illustrates the
259 variation in power output using the 3 turbine options considered here.

260

261 **Figure 4.** Long-term flow and head variation across three PRV sites. a) Thomas Court, 145 kW (1994 -
262 2013); b) Blackhorse Bridge, 75 kW (1996 - 2013) and c) Merrion Gates, 12.5 kW (1993 - 2013).

263

264 *4.2 Turbine Comparisons: Energy Recovery Potential and Investment Payback*

265 The impact of turbine selection on energy recovery and payback periods is presented in Table 2.
266 Estimated gross income was calculated assuming an annual power generation based on the design year
267 (i.e. performance was projected over the 20-year period based on a design flow from year 1 only, as
268 would be standard practice). Subsequently, actual gross income was determined, reflecting analysis of

269 the true fluctuations in power generation over the subsequent 16-19 years for each site. For the two-PAT
270 scenario, the percentage of time the smaller sized PAT was in use over the period is also shown.

271 Findings revealed that significant power generation capacity exists across each of the scenarios. The
272 Kaplan produced the greatest amount of energy across all sites, owing to its higher overall efficiency
273 compared to the PAT (as illustrated in Figure 3). However, the Kaplan cost approximately 25% more to
274 install than either a single PAT or two PATs system. This is in line with previous research which also
275 highlighted the lower cost of PATs when compared to conventional turbines (Williams 1996; Nautiyal
276 and Varun 2010). Furthermore, the cost difference was greater at the site with the lowest power output
277 potential (the Kaplan turbine cost 29% more than a PAT).

278

279 **Table 2.** Estimates of total energy generated, capital cost, estimated and actual gross income, payback
280 periods and smaller PAT viability for varying turbine scenarios across three PRV sites.

281

282 Acceptable payback periods were identified for those sites with medium and larger power
283 capacities, although the actual payback period was generally higher than the estimated payback across
284 these sites. The installation of a single PAT had the longest payback across all sites whilst the Kaplan
285 was the best turbine choice regarding the shortest payback period. However, the difference in payback
286 between the Kaplan and two PATs was only one year in total. In terms of the PRV with the smallest
287 power potential (Merrion Gates), only the two-PAT scenario was found to have an economically viable
288 payback period. Based on the design flow data (i.e. year 1 only), the initial payback estimates indicated
289 that none of the turbine scenarios would achieve a viable payback period. However, the effects of
290 considerable flow variation over the twenty years meant that the second smaller PAT was the best
291 choice turbine 52% of the time. Figure 5 illustrates the two-PAT scenario in greater detail indicating the

292 effects of long-term flow variation on turbine efficiency and viability. Evidently, this site exhibits high
293 flow variability and as the flow rate decreases, deviating from the turbine design flow of the larger PAT,
294 the second smaller PAT becomes the better choice in maximising efficiency and power output.
295 Interestingly, the smaller PAT was utilised less frequently across the larger PRV sites due to relatively
296 lower variation in flow conditions.

297 From an environmental output perspective, Table 3 highlights the total CO₂ emission savings from
298 electricity generation for each turbine option. The Kaplan achieved the greatest savings potential across
299 all PRVs and almost double that of a single PAT at Thomas Court PRV, the site with the largest power
300 output capacity.

301

302 **Figure 5.** Long-term annual flow variation and performance of a two-PAT scenario at Merrion Gates
303 PRV, displaying an annual breakdown of the percentage of time each PAT option was the near-optimal
304 choice in achieving maximum turbine efficiency. PAT 1 represents the larger PAT developed for the
305 design flow whilst PAT 2 is designed for 50% less than the design flow.

306

307 **Table 3.** Comparison of CO₂ emissions savings estimates for varying turbine scenarios across three
308 PRVs in Dublin.

309

310 **5 Discussion**

311 This research revealed the potential risks posed by long-term flow variation on energy recovery using
312 MHP installations into the future, thus highlighting the importance of this consideration when estimating
313 turbine suitability. The incorporation of high resolution flow and head data allowed for a more realistic
314 assessment of power potential over the long-term given the detailed diurnal, daily, seasonal and annual
315 fluctuations in flow rates which can influence turbine efficiency and viability into the future.

317 *5.1 Long-term Flow Variation Across Sites*

318 The analysis of long-term flow and head data across a number of PRVs identified considerable
319 fluctuations in flow conditions across sites, within the same small geographical region. Thus, site
320 characteristics such as the district type e.g. commercial or residential, play a strong role in overall
321 demand requirements. It was anticipated that demand would increase in line with economic and
322 population growth but not all sites reflected this. The smallest PRV, Merrion Gates, experienced a
323 reduction in demand during the 2000s. Such variation in flow conditions indicates the complexity in
324 determining an optimum design flow for a turbine. Thus, anticipating the challenge of long-term flow is
325 vital when assessing the potential feasibility of varying turbine options. Accordingly, in order to achieve
326 maximum energy recovery and long-term viability of such installations, improved flexibility in turbine
327 operation is essential where flow and head are expected to deviate substantially.

328

329 *5.2 Turbine Comparisons and the Role of PAT Technology in Accommodating Increased Flow* 330 *Variability*

331 In order to advance the uptake of MHP technology a viable installation must comprise a minimum
332 payback period, maximise power output and revenue generation and reduce CO₂ emissions.
333 Furthermore, it must have the adaptive capacity to accommodate changing flow conditions over the
334 long-term. The impact of long-term flow and head variation on estimated energy recovery and
335 investment payback periods across three turbine scenarios revealed some valuable insights.

336 Firstly, the conventional Kaplan turbine was the best choice in terms of payback periods at the PRV
337 sites with greater power output potential, whilst a single PAT installation had the longest payback across
338 all sites. The superior performance of the Kaplan was due to its higher overall efficiency as shown in

339 Figure 3. The Kaplan also maintained higher efficiency over a wider range of partial flows. However,
340 the payback period differed by only one year between the Kaplan and two-PAT scenario. In terms of
341 environmental benefit, the Kaplan produced the greatest reduction in CO₂ emissions; between 37% and
342 48% more than a single PAT and between 25% and 43% more than a two-PAT option when comparing
343 sites. Yet, a significant disadvantage with the Kaplan is that it costs 25% more to install when compared
344 to either a single PAT or two PATs in parallel and this cost differential increased even further when
345 assessing economic viability at the smallest PRV site. Furthermore, the miniaturisation of traditional
346 turbine types such as the Kaplan is known to be prohibitively expensive, rendering them unsuitable for
347 the large number of potential MHP energy recovery sites with small output capacities.

348 The limits of conventional turbines such as the Kaplan are evident at sites with smaller power
349 capacities. The findings indicated that the two-PAT scenario was the only economically viable option at
350 the Merrion Gates PRV site which had the smallest energy recovery potential of 12.5 kW and the
351 greatest flow variability. In contrast the single PAT displayed a significantly longer payback period of
352 16 years whilst the Kaplan had a payback of 11 years and considerable upfront costs. The notably cost
353 effective option of a PAT when compared to a Kaplan, allows for the possibility of integrating more
354 than one PAT in parallel with small additional costs. This turbine solution of multiple PATs with
355 varying design flows in order to cater for flow variation can improve the overall energy generation
356 potential of PATs and the low installation cost coupled with comparable payback periods when
357 compared to conventional turbines highlights its economic advantages.

358 Thus, the integration of PAT technology within water supply networks potentially opens up the
359 opportunity to harness untapped recoverable energy at MHP sites with smaller power generation
360 potential and in locations where there exists large hydraulic variability, sites which may previously have
361 been considered unsuitable for MHP. Indeed it is worth emphasising the importance of this finding
362 where recent research has highlighted that the majority of MHP energy recovery opportunities in water

363 networks in Ireland and the UK were located at PRVs (>67%) and the majority of these sites had small
364 power output capacities (2-20 kW) (Gallagher et al. 2015).

365

366 *5.3 Limitations and Areas for Further Research*

367 The simulation of hypothetical scenarios presented in the current study, where each turbine was
368 designed based on one year of historical data and its performance was assessed across the subsequent 16
369 to 19 years, was useful to examine performance variability over time. However, in practice, hydropower
370 turbine designers will not know the future flow rate or available head over the coming 20 year period,
371 making the design of turbines which cater for future flow variations difficult. The use of water demand
372 forecasting models have an important role to play here to enable the variation in flow at PRVs in water
373 distribution networks to be predicted over the long-term. Corcoran et al. (2016), recently outlined the
374 development of a model of water demand forecasting for MHP installations at PRV sites, where
375 temperature, economic growth, population change, leakage and water pricing were significant
376 influencing factors. This and/or other similar demand forecasting models are a required prerequisite to
377 the design of the two PAT system described here.

378 Furthermore, the current approach presented a two-PAT scenario in which the smaller PAT was
379 designed for 50% less than the design flow. In essence, a range of alternative design flows could be
380 incorporated (80%, 120%, etc.). Optimisation research of various design flow options, in terms of the
381 optimum number and size of PATs, would allow for improved decision making for utility managers
382 regarding the most economically advantageous PAT configuration. Ideally where flow is split between
383 two PATs to cater for flow variation, each PAT should be in operation closer to 50% of the time to
384 achieve a useful benefit from the use of a second turbine. However, such an optimisation requires a
385 prediction of future flow rates at a given site, which may be subject to large uncertainty.

386 A further limitation of the current work lies in the estimation of MHP cost, and particularly PAT
387 cost. PAT costs have been widely reported in literature as being 10-20 times less expensive than
388 conventional turbines and figures in the range of €115-€350/kW have also been published (Teuteberg
389 2010; Motwani et al. 2013; Caravetta et al. 2014b; Power et al. 2014). However a cost-head-power
390 relationship such as that described in Equation 3 for the Kaplan would predict PAT costs with more
391 confidence than the existing cost-power relationship. Further research is required to develop such a
392 relationship for PATs. In addition, future preliminary designs of micro-hydropower energy recovery at
393 PRVs, incorporating analysis of this nature would benefit from the incorporation of a sensitivity
394 analysis. In the absence of the aforementioned PAT cost model, a sensitivity analysis testing the impact
395 of uncertainties such as the cost of PATs, costs of Kaplans and cost of electricity, should be conducted.

396 Assuming that the electromechanical equipment comprise 30% of the total project cost is also
397 subject to error. Gallagher et al. (2015) recently highlighted that in the water network setting this
398 percentage of cost varied from 30% to 70% based on local flow conditions and the size of the
399 installation. However, as the absolute cost of each site is not the valuable contribution of this paper,
400 rather the relative impact of turbine choice at each site and across the sites, this assumption does not
401 adversely impact on the findings.

402

403 **6 Conclusion**

404 Micro-hydropower represents a viable pathway to a more sustainable system of water supply, yet uptake
405 of this technology remains low and sporadic due to a range of risk factors which include long-term flow
406 and head variations potentially impacting on economic viability assessments. The focus of this study
407 was to undertake a detailed investigation of the impact of long-term flow variability on turbine operating
408 efficiencies and power output across a number of turbine design scenarios over a twenty year period
409 using Dublin as a case study site. Findings revealed that considerable variation in long-term flow

410 conditions occurred over the 20 years, particularly at PRV sites with smaller power generation
411 capacities, while head levels did not vary to the same degree.

412 Following investment payback analysis, the Kaplan was found to have the shortest payback period
413 and achieved the largest saving in CO₂ emissions across both medium and large MHP sites. However,
414 neither the conventional turbine nor single PAT were found to be economically viable, at the most
415 commonly occurring, smallest PRV site. Although there was an evident reduction in power generation,
416 the two-PAT scenario proved to be economically viable despite the increased flow variability.
417 Furthermore, this option was almost comparable with the Kaplan in terms of payback period across the
418 remaining sites and had a significantly lower installation cost.

419 Therefore, the incorporation of multiple PATs in parallel represents a viable technology option
420 which demonstrates resilience and flexibility to future fluctuations in flow and head conditions,
421 enhancing the adaptive capacity of MHP systems into the long-term. Previous investigations examining
422 the available resources for MHP energy recovery have highlighted that the majority of potential MHP
423 sites lies in this small capacity range, similar to the Merrion Gates site examined here. Such sites would
424 not have been previously considered economically viable due to the extent of flow variation and low
425 power output.

426 The present study is of relevance for water utilities as it highlights an adaptive design option to
427 maximise energy recovery potential within water distribution networks. Accordingly, the findings
428 strengthen the evidence base for greater uptake of MHP technology and PATs.

429

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545

Table 1. An overview of flow, head and power output estimates for three PRVs in Dublin. Power estimates were based on varying Kaplan turbine efficiencies, where the turbine design flow/pressure was assumed to be the average of the data from year 1 of the record.

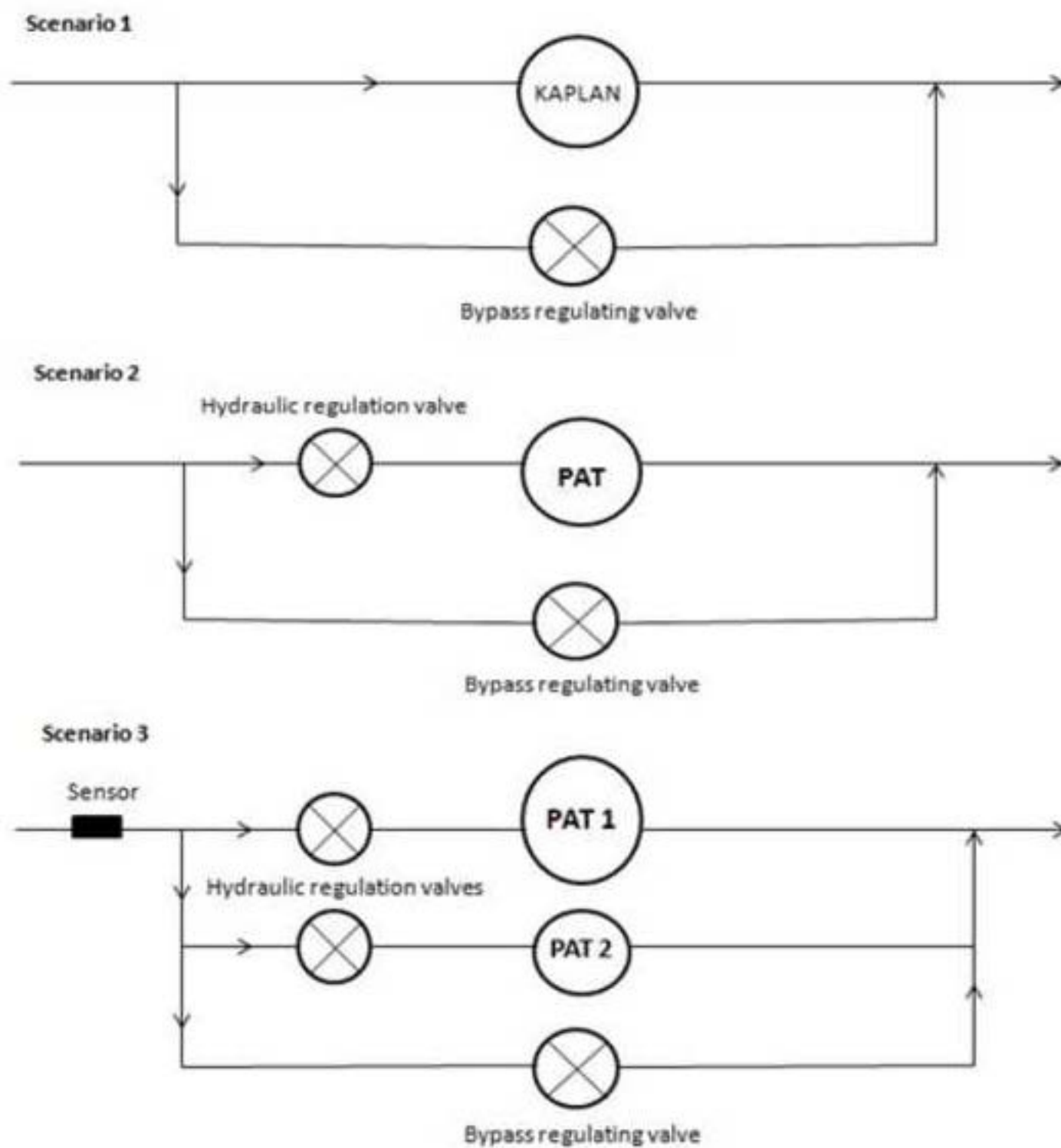
PRV Location	Flow (m ³ /s)	Head (m)	Estimated Power Output (kW)
Thomas Court	0.18	70.97	145.15
Blackhorse Bridge	0.24	43.9	75.44
Merrion Gates	0.32	7.84	12.5

Table 2. Estimates of total energy generated, capital cost, estimated and actual gross income, payback periods and smaller PAT viability for varying turbine scenarios across three PRV sites.

PRV Site	Turbine Scenario	Capital cost (€)	Estimated gross income (€/yr)	Estimated payback (Years)	Total Generation (kWh/yr)	Actual gross income (€/yr)	Actual payback (Years)	% of time smaller size PAT in use
Thomas	Kaplan	509,080	153,656	3	943,520	127,766	4	
Court	PAT	376,200	59,109	6	487,692	65,318	7	
(145 kW)	2 PATs	386,121	67,308	6	542,337	72,804	5	35
Blackhorse	Kaplan	409,392	83,272	5	875,574	118,458	5	
Bridge	PAT	306,921	63,830	5	554,964	74,534	6	
(75 kW)	2 PATs	317,095	66,927	5	586,298	80,323	6	26
Merrion	Kaplan	235,375	12,621	19	185,440	23,909	11	
Gates	PAT	168,129	9,387	18	103,879	12,735	16	
(12.5 kW)	2 PATs	169,813	10,164	17	139,003	17,547	10	52

Table 3. Comparison of CO₂ emissions savings estimates for varying turbine scenarios across three PRVs in Dublin.

PRV Site	Turbine Scenario	Total CO ₂ emissions savings (tonnes)
Thomas Court (145 kW)	Kaplan	8967
	PAT	4635
	2 PATs	5154
Blackhorse Bridge (75 kW)	Kaplan	7396
	PAT	4688
	2 PATs	4953
Merrion Gates (12.5 kW)	Kaplan	1860
	PAT	1042
	2 PATs	1394



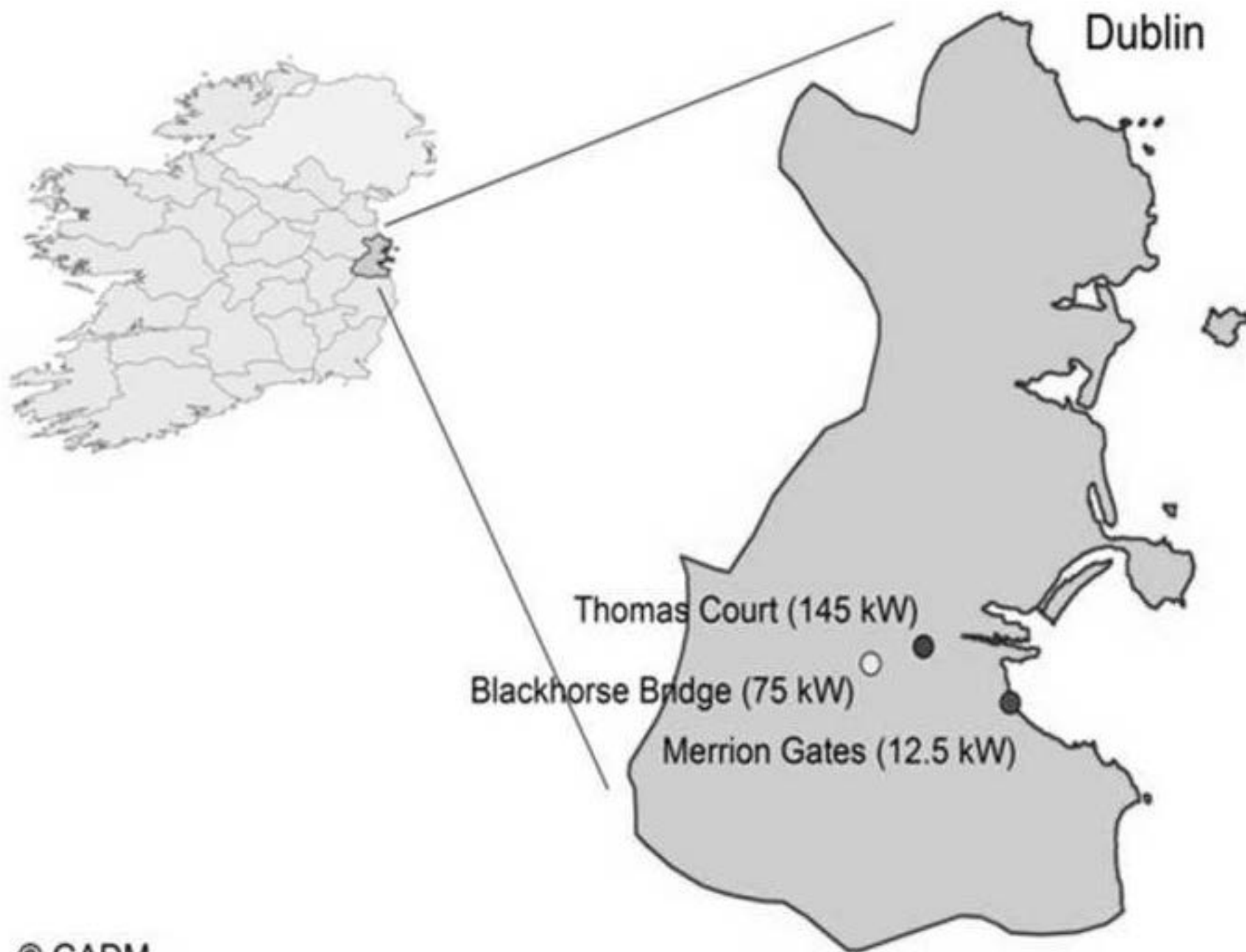
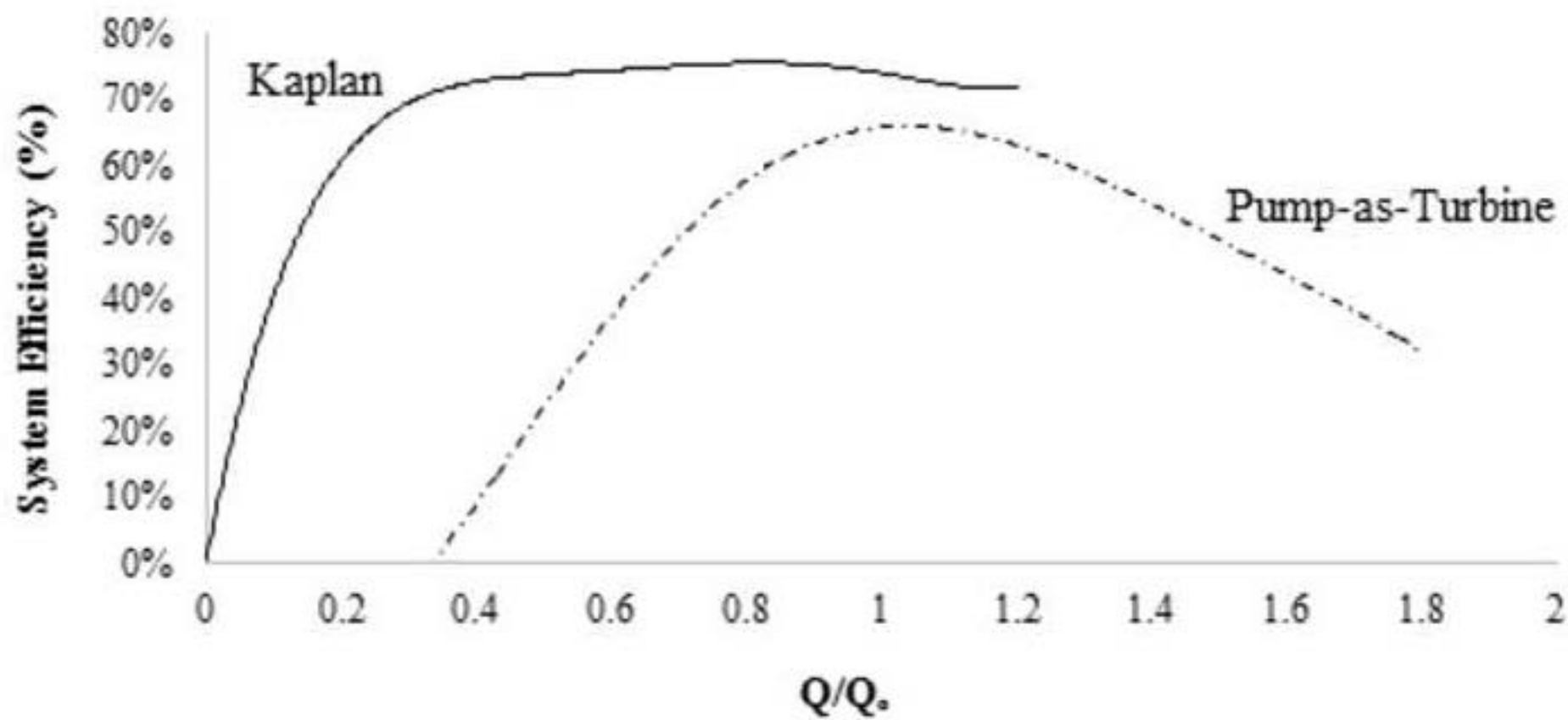


Figure 3



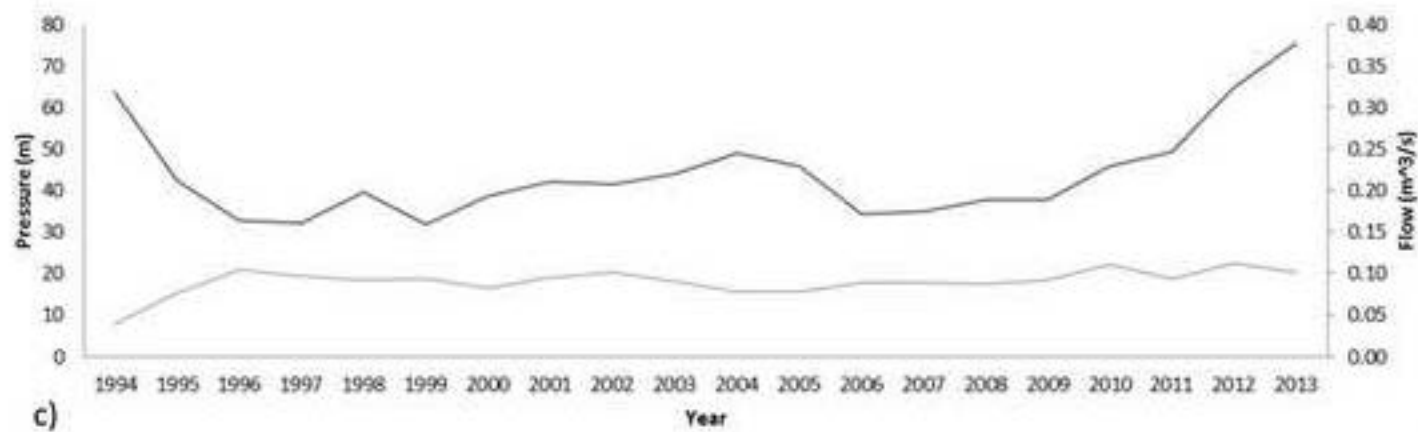
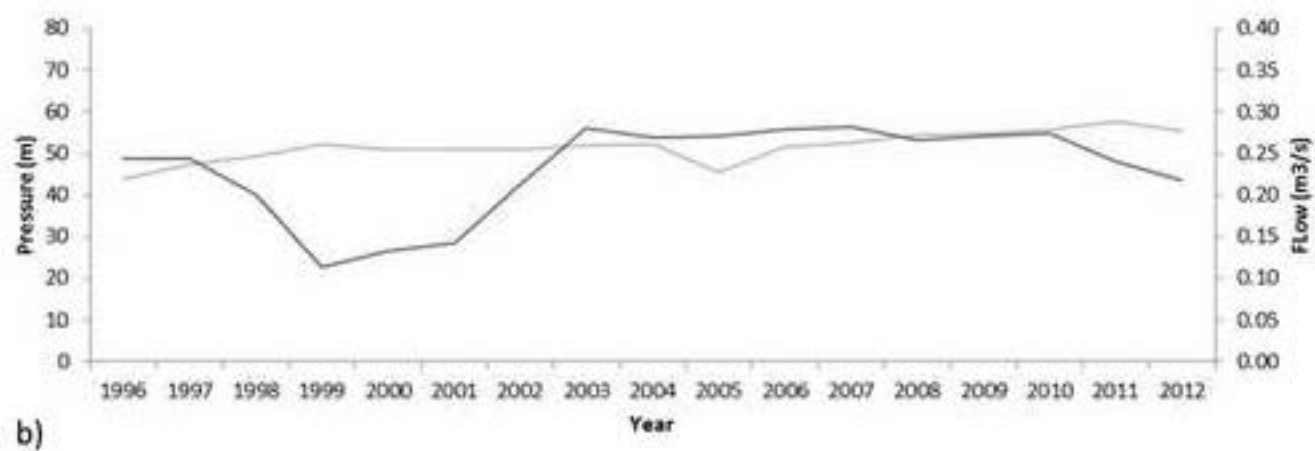
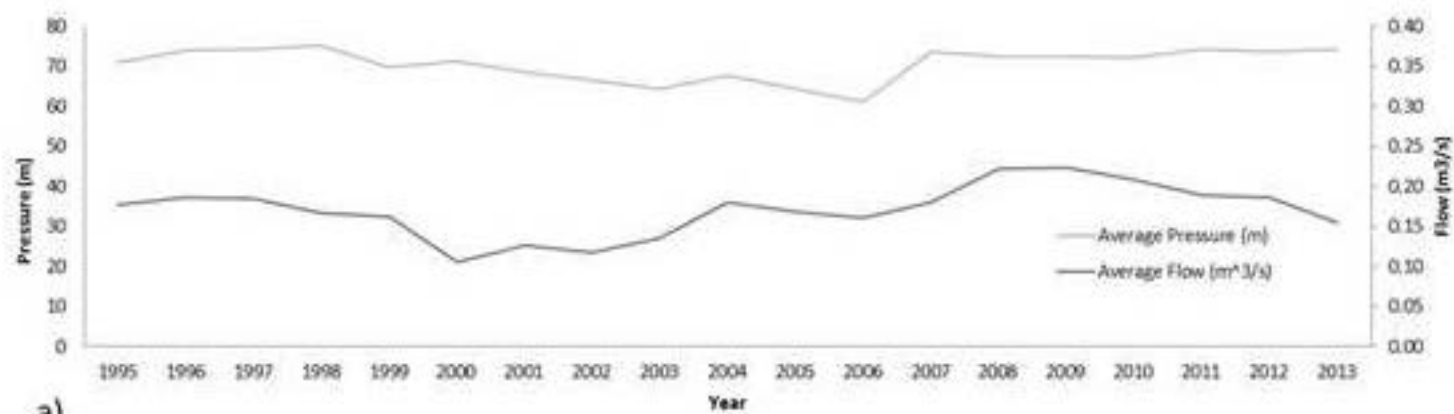


Figure 5

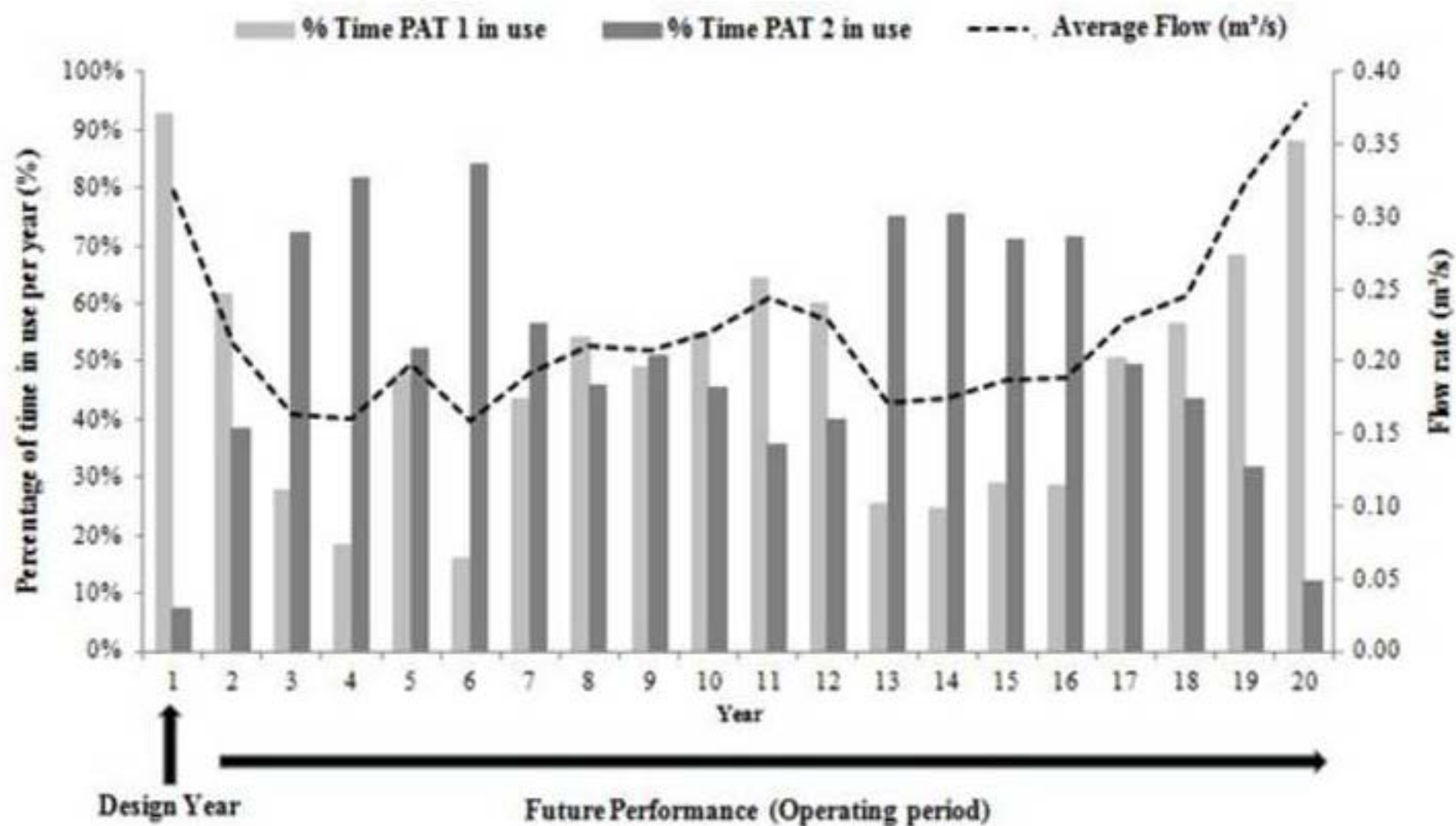


Figure 1. Installation schemes of three turbine scenarios; a Kaplan turbine, PAT and two PATs in parallel (Adapted from Carravetta *et al.* (2012)).

Figure 2. Map of the Dublin region displaying the location of the three pressure reducing valves used in the case study.

Figure 3. Overall system efficiency curves for the Kaplan turbine and PAT, assuming generator and transmission loss efficiencies of 85% and 98% respectively.

Figure 4. Long-term flow and pressure variation across three PRV sites. a) Thomas Court, 145 kW (1994 - 2013); b) Blackhorse Bridge, 75 kW (1996 - 2013) and c) Merrion Gates, 12.5 kW (1993 – 2013).

Figure 5. Long-term annual flow variation and performance of a two-PAT scenario at Merrion Gates PRV, displaying an annual breakdown of the percentage of time each PAT option was the near-optimal choice in achieving maximum turbine efficiency. PAT 1 represents the larger PAT developed for the design flow whilst PAT 2 is designed for 50% less than the design flow.

